Microwave SQUID multiplexer

K.D. Irwin
National Institute of Standards and Technology
Mail Stop 814.03
325 Broadway
Boulder, CO 80305

K.W. Lehnert
JILA
National Institute of Standards and Technology
Boulder, CO 80309

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K.D. Irwin
National Institute of Standards and Technology, Boulder, CO, 80305

K.W. Lehnert
JILA, National Institute of Standards and Technology, Boulder, CO, 80309

We describe a superconducting quantum interference device (SQUID) multiplexer operated at microwave frequencies. The outputs of multiple SQUIDs are simultaneously modulated at different frequencies and summed into the input of one high electron mobility transistor (HEMT). The large bandwidth and dynamic range provided by HEMT amplifiers should make it possible to frequency-division multiplex a large number of SQUIDs in one output coaxial cable. We measure low SQUID noise ($\sim 0.5\ \mu\Phi_0/\sqrt{\mathrm{Hz}}$ at 4 K) and demonstrate the multiplexed readout of two dc SQUIDs at different resonant frequencies. In this work, dc SQUIDs are used, but this approach is equally applicable to rf SQUIDs.

As arrays of SQUIDs have been developed for applications including low-temperature detector readout, the difficulty and cost of routing leads from each SQUID to room temperature have motivated efforts to cryogenically multiplex SQUIDs. Multiplexing of tens of low-bandwidth SQUIDs in a single output has been demonstrated using low-frequency multiplexing techniques. While these approaches have been successful, there is a need for a circuit that is capable of multiplexing thousands of SQUIDs in each output channel with the potential to allocate high bandwidth to each SQUID. To meet this need, we propose and demonstrate the microwave SQUID multiplexer.

A number of techniques have been developed to multiplex SQUIDs at low frequencies (up to a few megahertz on the multiplexed output channel). Time-division multiplexing (TDM), in which many SQUIDs are sequentially sampled, has been used for both dc SQUIDs (1) and rf SQUIDs (2), in both cases by use of a common flux-feedback coil for many multiplexed SQUIDs. Low-temperature detectors have also been frequency-division multiplexed by modulating them at different frequencies and summing all their outputs into one SQUID amplifier operated in a flux-locked loop (3). By use of low-frequency techniques, single chips have been developed that contain 1,280 multiplexed SQUIDs in 32 output channels (4). However, both the number of pixels that can be multiplexed and the maximum single SQUID bandwidth are limited by the low output bandwidth. Further, the filter elements used for low frequencies must be physically large. Non-multiplexed SQUIDs have been operated with excellent performance at microwave frequencies using resonant input coils (5), but these devices do not work at low frequencies. The microwave SQUID multiplexer described here provides large bandwidth in the multiplexed output channel but also input sensitivity down to dc.

Single rf SQUIDs are traditionally read out by modulating their outputs at a single rf carrier frequency (6). In the microwave SQUID multiplexer, each SQUID is placed in a resonant circuits with a unique microwave resonant frequency, and all resonant circuits are connected in parallel. A comb of microwave frequencies is used to simultaneously excite all resonant circuits. The amplitude and phase of the reflected microwave signal at each resonant frequency is a function of the magnetic flux in the associated SQUID, or the current through its input coil. The reflected signal from all SQUIDs is summed into the input of one cryogenic HEMT. Similar techniques have been used to multiplex the readout of single electron transistors (7) and kinetic inductance detectors (8). This microwave reflectometer readout is applicable to either dc or rf SQUIDs; dc SQUIDs are used in this letter.

Because SQUIDs have nonlinear periodic response functions, they are usually operated with flux feedback to linearize their gain. In large arrays, however, it is impractical to provide a separate feedback line to every pixel. The SQUIDs in the microwave SQUID multiplexer are operated open-loop, without feedback. Open-loop operation is appropriate for applications with moderate dynamic range requirements, including the readout of most low-temperature detectors. Unlike schemes that couple many detectors to one SQUID, the response of each SQUID in the microwave multiplexer can remain monotonic even with large signals in every detector. The signals are summed into a HEMT, which has large dynamic range. Operating open loop will lead to some non-linearity in the SQUID's response that must be corrected. Because the response of low-temperature detectors typically also has some nonlinearity, the software developed to correct the nonlinearity of the detectors can also be used to linearize the SQUIDs with no additional computational cost. Although the microwave SQUID multiplexer is operated without feedback, it is necessary to flux-bias the SQUIDs on an optimal region of their flux response functions. The microwave SQUID multiplexer will use a multiplexed flux-biasing circuit based on trapping flux in a superconducting flux-bias coil dedicated to each SQUID.

In this work, we present an initial demonstration of the microwave SQUID multiplexer. We measure good single-SQUID noise performance in a microwave reflectometer, and demonstrate the multiplexed readout of two dc SQUIDs at different resonant frequencies. In this initial work, we apply a dc flux bias to the SQUIDs using a separate line to each SQUID from room temperature – the multiplexed flux-bias circuit will be demonstrated separately.

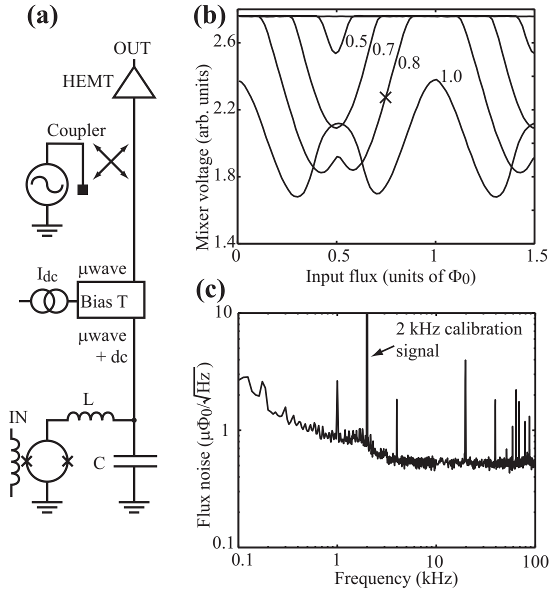

FIG. 1. (a) Circuit for microwave reflectometer readout of a single SQUID. (b) Reflected 545 MHz, -66 dBm microwave signal from a dc SQUID as a function of flux bias. Curves have different dc bias currents, listed in units of $2I_0$. The 'x' marks the bias point at which the noise spectrum in (c) is taken. (c) SQUID flux noise. A 1 mΦ_0 2 kHz calibration signal is injected into the flux line. The other lines are harmonics of 2 kHz and harmonics of 20 kHz injected by the mixer. The low-frequency noise is introduced by inadequate shielding of the HEMT bias circuit.

The chip used in these experiments has several identical SQUIDs with design values for two-junction critical current $2I_0$=100 µA and SQUID inductance L_{sq}=20 pH. The SQUID chip is wire-bonded to a custom printed-circuit board. In the first experiment, the output of a single SQUID is impedance-matched to a HEMT using an L-section resonant transformer consisting of a series inductance L provided by wirebonds to the SQUID chip and a parallel capacitance C formed by a 10 pF surface-mount capacitor and additional stray capacitance (Fig. 1a). The dynamic resistance of SQUIDs of this design typically varies between 2 Ω and 4 Ω, depending on the input flux and the bias. The circuit is designed to transform from SQUID dynamic resistance R_{in}=3 Ω to R_{out}=50 Ω with a resonant frequency of ~500 MHz, matched to the HEMT used in the experiment. A bias T is used to add a dc bias to the SQUID in addition to the microwave bias. The SQUID can be excited using any frequency in the 400-600 MHz region of optimum HEMT sensitivity.

A microwave signal generator produces a 545 MHz tone that is divided into two signals. One signal is connected directly to the local oscillator (LO) port of the mixer. The other signal is attenuated, phase shifted, and delivered to the coupled arm of a 30 dB directional coupler held at 4.0 K. The attenuated signal is then applied to the SQUID resonant circuit. The signal reflected from the SQUID is passed back through the direct arm of the coupler before being amplified by a cryogenic HEMT. After further amplification, the reflected signal is sent to the rf port of the mixer. The intermediate frequency output of the mixer is thus proportional to the amplitude of the reflected 545 MHz tone. The phase of the incident microwave tone is adjusted so that the reflected microwave signal was in phase with the LO signal.

We investigated the performance of the SQUID at three microwave power levels (-76 dBm, -66 dBm, and –56 dBm), and a range of dc bias currents and flux levels. Fig. 1b shows the mixer voltage as a function of the input flux for the –66 dBm power level. When 100 µA dc bias current is applied to the SQUID, the maximum integral nonlinearity of the mixer output with respect to a flux input to the SQUID is < 0.1% for a maximum flux excursion of 0.02 Φ_0, and < 8% for a maximum flux excursion of 0.2 Φ_0.

A noise spectrum of the mixed-down signal is shown in Fig. 1c, referred to a flux noise at the SQUID input. The measured white noise level is ~0.5 $\mu\Phi_0/\sqrt{\text{Hz}}$. Significant 1/f noise is observed below 1 kHz. Measurements indicate that the noise is introduced through inadequately shielded HEMT amplifier bias lines, and is not a characteristic of the SQUID, so it should be possible to significantly reduce the 1/f noise. At –76 dBm microwave power the white noise level is slightly lower, ~0.4 µΦ_0/rt(Hz),but the flux dynamic range is much smaller. Noise measured at –56 dBm microwave power is ~0.8 µΦ_0/rt(Hz).

The fractional bandwidth of an L-section transformer with the designed impedance transformation is (9) $Q = \left(R_{out}/R_{in}\right)^{1/2} = 4$. A much higher Q than this is required for multiplexed readout. Higher Q can be provided by a parallel resonant circuit.

In the second experiment, two separate SQUIDs are placed in parallel resonant circuits with different resonant frequencies near 500 MHz (Fig. 2). The inductances L1 and L2 are provided by lengths of superconducting wire designed to have slightly different inductances near 8 nH. A dc bias current is applied in series to both SQUIDs through resistors designed to isolate the two circuits at high frequencies. In future experiments, the bias resistors will be replaced by inductors to reduce power dissipation. The resonant circuits are designed to have unloaded Q of 100 and loaded Q of 50, and to match the impedance of the HEMT.

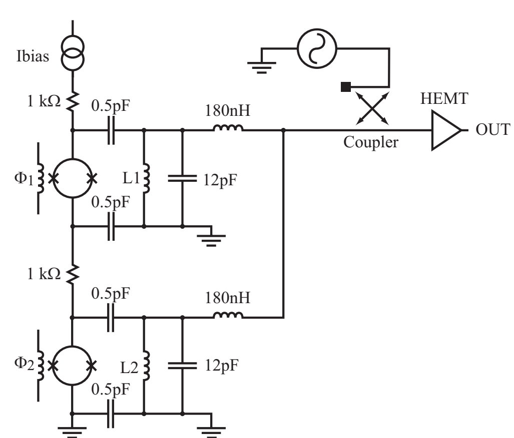

FIG. 2. Resonant circuit for multiplexed readout of two SQUID pixels.

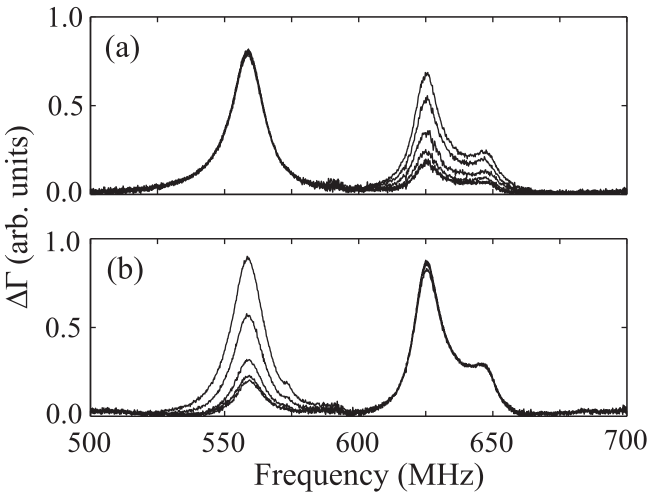

FIG. 3. Differential measurement of the scattering of a microwave signal off the circuit in Fig. 2, relative to the signal when the SQUIDs are off. Data is shown as a function of frequency. (a) A family of curves for different flux in SQUID 1. (b) A family of curves for different flux in SQUID 2. The small crosstalk is due to flux signal crosstalk on the inputs of the two SQUIDs.

The power reflected from the SQUID resonant circuits is measured with a network analyzer. Figs. 3a and 3b show a differential measurement of the reflected power as a function of frequency with a 100 μA dc bias current, with respect to the case with no dc bias current (SQUIDs in the superconducting state). A –80 dBm microwave power is used. Resonances at 560 MHz and 625 MHz are observed, reasonably close to the design value near 500 MHz. The measured Q of the resonances is about 60, also close to the design loaded Q value of 50. In Fig. 3a, a family of curves is shown for different flux input Φ_1 to SQUID 1. In Fig. 3b, a family of curves is shown for different flux input Φ_2 to SQUID 2. The small crosstalk between the two SQUIDs agrees both in sign and magnitude to estimates of the inductive crosstalk expected at the inputs of the two SQUIDs, which are not designed to be well isolated. The high-frequency shoulders on the peaks are not well understood – they may be due to reflections in the non-ideal surface-mount inductors and capacitors or due to reflections off the HEMT, which is not well matched to 50 Ω above 600 MHz.

The experiments presented here use dc SQUIDs that dissipate ~1 nW per SQUID. If operated at very low temperatures, this power dissipation is too high for very large arrays. By a simple redesign, the power dissipation of these dc SQUIDs can be reduced by one to two orders of magnitude. For very large arrays, we are developing non-hysteretic, unshunted rf SQUIDs (10) that can have excellent noise performance, and can dissipate less than 1 pW per SQUID.

In order to multiplex large arrays of SQUIDs, it will be necessary to operate at higher frequency, to lithographically pattern the resonator elements on the same chip as the SQUIDs, and to achieve higher resonant Q. We have designed lithographic lumped-element resonant circuits using parallel-plate capacitors and spiral inductors to operate at 5 GHz. Planar three-dimensional modeling software predicts Q > 1000 and parasitic self resonances at frequencies above 8 GHz for all components. We can also design circuits with Q>1000 at 5 GHz using meandering quarter- and half-wave resonators and stub transformers, similar to the structures used to multiplex microwave kinetic inductance detectors (8). The design of circuits with Q > 100,000 should be possible using non-hysteretic SQUIDs, allowing many thousands of SQUIDs to be multiplexed in each HEMT amplifier channel.

The microwave SQUID multiplexer allows the readout of very large arrays of low-temperature detectors in a small number of HEMT amplifier channels. It is ideal for detectors requiring large bandwidth per pixel (such as TES optical detectors (11)), and can be used with any sensor that can be read out using SQUIDs (including TES x-ray and millimeter-wave detectors and magnetic calorimeters). It may also be applied to arrays of SQUIDs for magnetoencephalography (12) and non-destructive evaluation (13).

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